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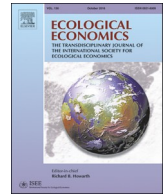
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## Analysis

## International trade and air pollution damages in the United States

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## ABSTRACT

This paper investigates the health and economic consequences of trade due to various air pollutants embodied in exports and imports. We compare the US emissions generated for US exports and those that were avoided by importing. An input–output framework of the US economy is employed together with a comprehensive database on damages (expressed in monetary terms) generated by pollutants, as estimated by Muller et al. (2011). We find that damages associated with international trade in 2002 were considerable. The net result is that damages were avoided through trade and that these avoided damages amounted to 2.7% of the US trade deficit and 3.4% of the US value-added associated with trade. Moreover, the computed “damage to value-added ratios” differed greatly across industries. Exports in some industries are so hazardous that more than half of the value-added gained from extra exports disappeared due to environmental damages. These findings imply that the US might benefit more from trade by increasing its exports more in low damage-intensive products than in high damage-intensive products.

## 1. Introduction

Reports by the US Environmental Protection Agency (EPA) show that emissions of air pollutants in the US decreased substantially since 1980. Such improvements are often linked to stricter regulations and improved environmental efficiency of production processes (Chestnut and Rowe, 1990; USEPA, 1999, 2011). Empirical studies, however, indicate that the stabilization of emissions in developed countries like the US has partially been due to growing imports from developing countries. Weber and Matthews (2007), for example, find a large increase of the relocation of US air emissions to other countries, between 1997 and 2004. These are caused by increasing quantities of products imported by the US.

Much of the existing research on emissions relocation via international trade has focused on emitted quantities of pollutants. In contrast, this study analyzes the impacts of the relocated emissions in terms of monetary values. Air pollutants are responsible for many adverse environmental effects, such as photochemical smog, acid rain, death of forests, and reduced atmospheric visibility. Polluted air can also directly harm human health, cause damages to property, and reduce agricultural productivity. The United States reduces its home damages when it imports products from abroad instead of producing these products domestically. In the same vein, the US increases its home damages when it produces for export purposes.

What are the benefits of using monetary terms in the impact assessment? First, using a common monetary unit allows for direct comparisons of damages generated by various air pollutants and computation of the total effects of all air pollutants. Second, unlike physical indicators, monetary indicators provide a natural link between the economic and the environmental consequences of trade. This implies that agents in the trade policy arena can compare alternative policies on the basis of indicators that internalize negative external effects of production activities. Of course, monetary valuation has its own limitations and involves the use of subjective prices for these externalities. Still, previous studies provide useful estimates in this respect.<sup>1</sup>

This study investigates the net damage changes through international trade for the US economy in 2002. That is, we estimate the environmental damages in the US generated by its exports and subtract the damages in the US if its imports would have been produced at home. To this end, we employ a detailed input–output (IO) table for the US economy (needed to take the required US production of raw materials, parts and components and business services into account), complemented by a comprehensive database on the damages generated by additional emissions of several air pollutants. These emission damage values were estimated by Muller et al. (2011), using the so-called Air Pollution Emission Experiments and Policy (APEEP) model. The six major local air pollutants included in their study are SO<sub>2</sub>, PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>x</sub>, VOC, and NH<sub>3</sub>. We cannot but limit our analysis to the US, in view

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of two data constraints. First, Muller et al.'s (2011) estimates of the damages of emissions in monetary terms are very specific for the US. Second, we do not have IO tables at the same level of detail (400 industries) for the majority of the most important trade partners of the US. Hence, our results do not address the impacts of US trade elsewhere in the world.

This paper is structured as follows. After discussing the background of this study in Section 2, the details of our approaches are described in Section 3. Section 4 discusses the data we used in this study. Section 5 is devoted to the main results. We report on sensitivity analyses in Section 6, and present conclusions in Section 7.

## 2. Background

Global environmental challenges have prompted increased attention to the environmental performance of individual countries, for example in relation to pledges made by countries in various international treaties. Such a focus disregards that the growing intensity of international trade in both intermediate inputs and final products has led to increasing differences between the location of emissions and the location of the use of the associated final products: substituting domestically produced goods by imports contributes to reducing domestically emitted pollutants, but increases these elsewhere. There is a growing literature on environmental degradation focusing on these emissions relocated by trade (see the comprehensive surveys of Jayadevappa and Chhatre, 2000; Wiedmann et al., 2007; and Sato, 2012). One of the earliest empirical contributions was Walter (1973). Recent studies employ global input-output tables that allow for more accurate estimations of traded emissions (e.g., Davis and Caldeira, 2010; Peters et al., 2011; Moran et al., 2013).

Another part of the literature on environmental degradation focuses on “emission-damage analysis”. Emission-damage analysis has been widely used to evaluate social impacts of policy changes related to emissions. For instance, USEPA (2011) analyzed benefits due to the reduction of emissions as a consequence of the Clean Air Act. It found that the total estimated direct benefit (related to human health and welfare) in the year 2010 amounted to around \$1300 billion. Furthermore, it estimated the total present value of direct benefits from the Clean Air Act from 1990 to 2020 to be about \$12 trillion.

In this study, we demonstrate that combining the literature on emissions embodied in trade and the literature on damages yields additional insights. We connect the two strands of literature and estimate the monetary consequences of emissions in the US implied by its exports and of emissions that have been “avoided” by importing rather than producing at home.

Muller and Mendelsohn (2007, 2009) used a so-called Air Pollution Emissions Experiments and Policy (APEEP) model to calculate the marginal damage associated with emitting an additional ton of pollution in the US. Air emission data used by the authors were provided by the US Environmental Protection Agency's National Emission Inventory (NEI), which encompasses all anthropogenic emissions of six air pollutants ( $\text{SO}_2$ ,  $\text{PM}_{2.5}$ ,  $\text{PM}_{10}$ ,  $\text{NO}_x$ ,  $\text{VOC}$ , and  $\text{NH}_3$ ) in the 48 contiguous states of the US (USEPA, 2006, 2009). The APEEP model first connects emissions of air pollutants to physical effects. These physical effects include adverse effects on human health, decreased timber and agriculture yields, reduced visibility, accelerated depreciation of materials, and reductions in recreation services. In the next step, the model translates the physical effects into monetary terms using standard estimates of mortality and morbidity risks, market values of goods and services, and results of other valuation studies (e.g. Chestnut and Rowe, 1990; McClelland et al., 1991).

Muller and Mendelsohn (2007, 2009) first calculated baseline damages of the emissions in 2002 emissions, and then calculate damages of one additional ton of emission. They followed this procedure for each of the six pollutants in each of 10,000 locations that act as sources of pollution, such as factories. The estimated marginal damage,  $MD_{s,j}$ ,

indicates the value of damages caused by one additional ton of pollutant  $s$  in location  $j$ . Muller and Mendelsohn (2007) compared the gross damages to value added ratios by industry. They found that these ratios were larger than one in six industries (Stone Quarrying, Solid Waste Incineration, Sewage Treatment Plants, Oil and Coal Fired Power Plants, Marinas, and Petroleum-Coal Product Manufacturing). This implies that the environmental impacts of production can be so large that their monetary value exceeds the direct economic impacts. Muller and Mendelsohn (2007) also found that emissions of  $\text{VOC}$ ,  $\text{NH}_3$ ,  $\text{SO}_2$  and  $\text{PM}_{2.5}$  generated about 80% of total damages, although they account for only half of all emissions in terms of weight.<sup>2</sup> Muller and Mendelsohn (2009) used these data on source-specific marginal damages to identify more efficient market-based pollution policies: They calculated the welfare gains from making the US trading program in sulfur dioxide allowances for power plants more efficient.

Based on these data from Muller and Mendelsohn (2007, 2009), Muller et al. (2011) presented a framework to include environmental impacts into the system of national accounts. They estimated the air pollution damages for each industry in the United States. In Muller et al. (2011), gross external damage by industry is calculated by multiplying the industrial emissions in each location to the pollutant-specific marginal damage in the same location. In this study, we divide these industry-level gross external damage indicators by industry-level gross output figures. In the next section, we discuss how these ratios (or damage coefficients) can be used to estimate the effects of US trade on pollution damage in this country, using input-output analysis.<sup>3</sup>

## 3. Methods

In this study, we use input-output analysis. Input-output analysis explicitly takes into account that exporting products requires intermediate inputs, the production of which might have environmental impacts. A simple, highly stylized illustration is given in Fig. 1. The production of cars to be exported from the US requires activities in the automotive industry. Besides labor, capital and possibly damaging emissions, these activities require components produced by, for example, the machinery industry. The (potentially polluting) activities in this industry require inputs from the metals and mining industries. Hence, damages are not only generated in the automotive industry itself (D3 in the figure), but also in other industries (D1 and D2). Indirect effects like these should be taken into account in the quantification of damages due to trade.

This study focuses on local pollutants and we calculate the effects in the US using the national IO table. Since we are interested in damages occurring on US soil (and the avoidance of such damages by US imports) rather than the environmental impacts of US production or consumption on the rest of the world, we should use information on the US production structure. An advantage that comes with these limited data requirements is that using the US input-output account data allows us to estimate damages at a detailed level of industry detail. The US input-output tables from the Bureau of Economic Analysis (BEA) contain data for more than 400 industries, which implies that we can meaningfully link them to the also detailed damage data.

<sup>2</sup> Previous studies, such as Fann et al. (2009) and Levy et al. (2009), find evidence of heterogeneity among pollutants, too. However, both studies had scopes that are somewhat different from Muller and Mendelsohn's (2007, 2009). Fann et al. (2009) computed damages per ton for 9 urban areas rather than for the whole country. Levy et al. (2009) focused entirely on coal-fired power plants, so only one industry was covered by their study.

<sup>3</sup> In our analysis of the damages that are avoided by importing products, we do not include so-called “non-comparable imports”. These are imports of products that US industries cannot produce themselves, like specific raw materials. Hence, analyzing what would happen if these products would be produced in the US is not meaningful. Just for information, the share of non-comparable imports in the value of total imports amounted in 2002 to roughly 10%.

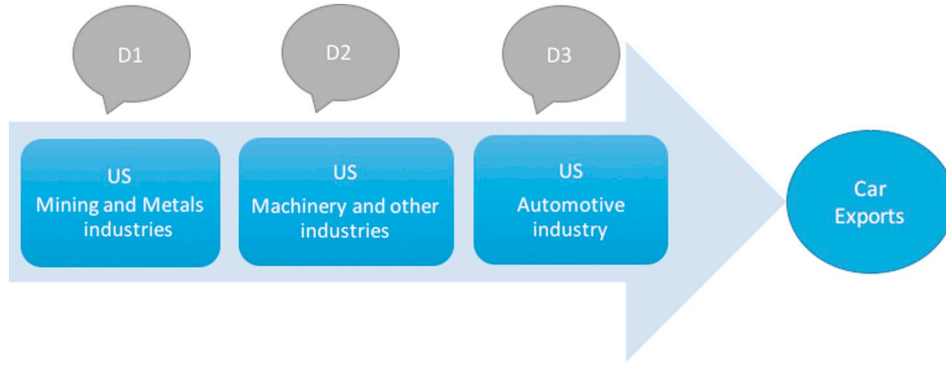


Fig. 1. Industries involved in final demand of a US-produced car.

Using an input-output table for the US, we obtain a vector of output changes for each industry due to a dollar of final demand (i.e. household consumption, private investment, government expenditures or exports) for the output of industry  $i$ . It is expressed as  $(\mathbf{I} - \mathbf{A}_{\text{US}})^{-1} \delta^i$ , where  $\mathbf{I}$  is the identity matrix,  $\mathbf{A}_{\text{US}}$  is the industry-by-industry direct domestic input coefficient matrix for the US, and  $\delta^i$  is a column vector with the  $i^{\text{th}}$  element equal to one and zeros elsewhere. The matrix  $(\mathbf{I} - \mathbf{A}_{\text{US}})^{-1}$  is usually called the Leontief inverse. It takes the indirect effects depicted in Fig. 1 into account.

For pollutant  $s$ , we define “unit damage” as the damage generated by one dollar of final demand for the output of industry  $i$  and denote it by  $UD_{s,i}$ . In a similar vein, we define “unit value-added” as the value-added generated by one dollar of final demand for industry  $i$ 's product. We denote it by  $u_i$ . We have

$$UD_{s,i} = \mathbf{d}'_s (\mathbf{I} - \mathbf{A}_{\text{US}})^{-1} \delta^i, \quad (1)$$

$$u_i = \mathbf{v}' (\mathbf{I} - \mathbf{A}_{\text{US}})^{-1} \delta^i, \quad (2)$$

in which  $\mathbf{d}_s$  is the damage coefficients vector that gives—for each of the industries—the damages in dollars related to pollutant  $s$  per dollar of gross output, and  $\mathbf{v}$  is value added coefficient vector that gives the value added per dollar of gross output.<sup>4</sup>

The damage coefficients vector  $\mathbf{d}_s$  has been computed in a number of steps:

$$d_{s,i} = GED_{s,i}/x_i, \quad (3)$$

in which  $x_i$  is the gross output in dollars in industry  $i$  and  $GED_{s,i}$  denotes the dollar value of damages attributed to pollutant  $s$  generated by industry  $i$ . To obtain  $GED_{s,i}$ , we aggregated the  $GED_{s,i,j}$  in Muller et al. (2011) across locations  $j$ :

$$GED_{s,i} = \sum_j GED_{s,i,j}, \quad (4)$$

As mentioned in Section 2, Muller et al. (2011) calculated the  $GED_{s,i,j}$  by multiplying the industrial emissions in each location to the pollutant-specific marginal damage in the same location. Therefore, we can re-write Eq. (4) as:

$$GED_{s,i,j} = E_{s,i,j} MD_{s,j}. \quad (5)$$

where  $E_{s,i,j}$  is the industrial emissions of pollutant  $s$  in location  $j$  in industry  $i$ , and  $MD_{s,j}$  is the marginal damage of pollutant  $s$  in location  $j$ .

Eqs. (1) and (5) yield  $d_{s,i} = \sum_j (MD_{s,j} E_{s,i,j})/x_i$  and reflect an important assumption in this study. To estimate “unit damages”, we assume that the shares of locations in the emissions of all industries directly and indirectly involved in the production of one dollar of final output of industry  $i$  are equal to the industry averages. For example, if the US exports of cars are increased by 2%, we implicitly assume that factories all over the US will increase their production of cars by 2%

and the same is assumed regarding the intermediate inputs for cars. Most likely, this assumption is far from true, since exported products might generally well be produced closer to borders and ports than products for domestic markets. Since the marginal damages  $MD$  in Eq. (5) are dependent on location  $j$ , our results for  $UD$  in (1) would be biased if exported products would tend to be produced in locations with marginal damages that are far from the average. We would need an interregional input-output table (with fine-grained geographical detail) to relax this assumption, but such a table is not available for the US.

The elements  $v_i$  of the value added coefficients vector  $\mathbf{v}$  (see Eq. (2)) are computed as

$$v_i = va_i/x_i, \quad (6)$$

in which  $va_i$  is the value-added of industry  $i$  and  $x_i$  is the gross output in industry  $i$ . The required information is available in the input-output table itself.

Having defined “unit-damage” and “unit value added”, we can calculate damages associated to producing exports and damages avoided by imports. Damages generated by producing exports of the output of industry  $i$  are denoted by  $DEX_{s,i}$ :

$$DEX_{s,i} = UD_{s,i} e_i, \quad (7)$$

in which  $e_i$  is the value of US industry  $i$ 's exports. The total amount,  $\sum_i \Sigma_i DEX_{s,i}$ , can be interpreted as the damages in the US associated with production to meet demand from other countries. We assume that traded and non-traded products are produced in the US using the same input mix, which is an assumption often adopted in input-output analyses. To relax this strict assumption, input-output tables in which industries are split into sub-industries producing export products and producing products for domestic markets (based on firm-level data) would be needed. Such tables are not available for the US through official data sources.<sup>5</sup>

Next, we analyze the impacts of imports, by estimating the damages avoided by importing. Everything else equal, purchasing foreign goods and services rather than producing these at home reduces damages in the US. How much additional damages would the US have faced if it had not relied on any imports? We adopt an approach that is identical to Levinson's (2009), who focused on reduced pollution volumes. The avoided damages due to pollutant  $s$  in the US through importing goods and services produced by industry  $i$  in foreign countries are

$$DIM_{s,i} = UD_{s,i} m_i, \quad (8)$$

in which  $m_i$  is the value of imported products (of both final products and intermediate inputs) from foreign counterparts of industry  $i$ .

The impacts of exports and imports on value added changes in industry  $i$  are denoted as  $VEX_i$  and  $VIM_i$ , respectively:

<sup>5</sup> Very recently, BEA has published a report on its efforts to construct an input-output table in which data for multinational firms and for non-multinationals have been separated (see Fetzter et al., 2018).

<sup>4</sup> Primes stand for transposition.



$$VEX_i = u_i e_i, \quad (9)$$

$$VIM_i = u_i m_i. \quad (10)$$

We define the net costs of trade in the output of industry  $i$  regarding pollutant  $s$  as the difference between  $DEX_{s,i}$  and  $DIM_{s,i}$  and denote it as  $\Delta D_{s,i}$ :

$$\Delta D_{s,i} = DEX_{s,i} - DIM_{s,i} = UD_{s,i}(e_i - m_i). \quad (11)$$

In a similar vein, we define the net value added gain of trade in the output of industry  $i$  ( $\Delta VA_i$ ) as the difference between  $VEX_i$  and  $VIM_i$ :

$$\Delta VA_i = VEX_i - VIM_i = u_i(e_i - m_i). \quad (12)$$

#### 4. Data

We use the gross external damages (GED) for 2002 as estimated by Muller et al. (2011). They employed emissions to air data from the US Environmental Protection Agency's national emission inventory (USEPA, 2006, 2009). This covers all anthropogenic emissions of six air pollutants ( $SO_2$ ,  $PM_{2.5}$ ,  $PM_{10}$ ,  $NO_x$ ,  $VOC$ , and  $NH_3$ ) in the 48 contiguous states of the US (i.e., excluding Alaska and Hawaii). The GED data are available for about 840 industries (at the six-digit level in the North American Industry Classification System, NAICS). This implies the number of air pollutants considered (indexed with  $s$ ) is 6, the number of industries (indexed with  $i$ ) is about 840, and the number of states (indexed with  $j$ ) is 48.

To account for indirect effects (output of intermediate products to be used in other industries), we employ Input-Output Accounts (make and use tables) data from the BEA. Given that damages data are only available for 2002, we use the IO table for the same year. The details of the procedures to arrive at the IO table from the make and use tables can be found in Appendix A, but two aspects are too important to be left undiscussed here.

First, we remove imported intermediate inputs from the use table. The use table is a matrix that shows the use of products by each industry and by final users. The inter-industry commodity flow data used to construct the US use table do not distinguish between the use of domestically sourced products and products purchased abroad. Since we focus on damages in the US, removing the imported intermediate products is a necessary step. To attain this, we use an import matrix from the BEA. The import matrix documents the values of uses of imports by industries and final users, by product.<sup>6</sup>

The second issue relates to the matching of the industry classification of the IO table to the NAICS industry classification of the damages data. The US IO table contains data for 426 industries.<sup>7</sup> As we mentioned above, emissions and damages data are available for many more industries. Aggregating the more detailed industries in the emissions data into the broader industries in the IO data proved unproblematic in most cases (apart from the fact that aggregation bias is inevitable as soon as we start attributing damages to exports or imports). There are two categories of exceptions, however. First, we have 20 IO industries to which we cannot match any NAICS industry. This implies that we do not have information on damages for those 20 IO industries. In the baseline model, we assume that damages in these 20 industries are equal to zero. Another category of exceptions relates to agricultural industries and construction industries, for which the damages data contain less industry detail than the IO table. Disaggregating GEDs is

necessary with respect to those industries.<sup>8</sup> In the baseline model, we simply allocate GEDs in agricultural and construction industries proportionally to value added.<sup>9</sup> In Section 6, we report on sensitivity analyses to assess the extent to which results change if we adopt alternative approaches to deal with these issues.

For expositional reasons, we aggregate our analytical results for IO industries into 42 sectors.<sup>10</sup> Hereafter, we refer to the 6-digit IO industries as 'industries', and refer to the 42 aggregated IO sectors as 'sectors'. In addition, we sometimes aggregate results for the 42 sectors into results for three broad aggregates: the primary sector, the secondary sector, and the tertiary sector (see Table A6 in Appendix C for the aggregation of the 42 sectors into three).

We also addressed several issues with respect to prices. The first price issue is about the type of prices in which the IO table is expressed. It would be optimal to use data in basic prices. The basic price is the price received by the producer for goods and services that are sold, excluding taxes and subsidies. The make and use tables from the US BEA, however, are expressed in producers' prices (which equal the basic prices plus taxes on products minus subsidies on products). Tables in basic prices are not available from public US official sources and would have to be estimated. Therefore, the IO table in producers' prices is used. Part of our robustness analysis assesses the sensitivity of our results to the choice of a price concept: We repeat our analysis using the 2002 US IO table in basic prices obtained from the 2013 release of the World Input-Output Database (WIOD) (Dietzenbacher et al., 2013). This table is much more aggregated, however. It contains 35 sectors, based on the European NACE classification. Detailed discussions can be found in Appendix D.

The second issue relates to the price concepts used for imports and exports. The exports data as published in the BEA IO table are in producers' prices, which is the same as is used for all domestically produced commodities. Imports, however, are expressed in two different prices: the "foreign border prices" and the "US border prices". The foreign border price of imports is the value of commodities at the foreign port. Usually, it referred to as the "fob (free on board) price". The US border price is the price of a product when it enters the US, which is equal to the foreign border price plus transportation costs, insurance and custom duties. An internationally more common label for this price concept is the "cif (cost, insurance and freight) price". According to Horowitz and Planting (2009), the US border prices are comparable to producer prices of US domestic production. Therefore, in the baseline model, we use imports valued in US border prices. To assess the sensitivity of our results, we also present the results for imports in foreign border prices in Appendix D.

The third price issue is about changes in prices over time. The damage values taken from Muller et al. (2011) are expressed in dollars of 2000. The input-output tables from BEA, however, are expressed in prices of 2002. In the baseline analysis, we convert damage values to values in 2002 prices, using GDP deflators. We choose to use the Federal Reserve Bank's Implicit Price Deflator of GDP.<sup>11</sup> Damages involve aspects that have an impact in several spheres of the economy, including human health, agricultural productivity, visibility, and recreation. We feel that using a "broad" deflator like the GDP is more appropriate than using a specific deflator like the consumer price index or the industry-level output deflator. Inflation between 2000 and 2002 as measured using this GDP deflator amounted to 3.71%. Hence, total GED

<sup>6</sup> Horowitz and Planting (2009) give a more detailed discussion on this "domestication" issue, especially for the description and construction of the import matrix.

<sup>7</sup> Our analyses are based on 418 industries. We left out the industries that are called "Special industries" in BEA publications. For these industries damages data are not available. Most of these industries are government enterprises, which are only marginally involved in international trade and mainly supply to domestic final users.

<sup>8</sup> Alternatively, we could have aggregated industries in the IO table, but that would have meant a neglect of interdependencies between the industries involved.

<sup>9</sup> The procedures to handle these two exceptional categories are explained in more detail in Appendix B.

<sup>10</sup> We aggregate the results after having conducted the analysis. Aggregating data before doing the analyses would yield aggregation errors.

<sup>11</sup> See <http://research.stlouisfed.org/fred2/series/GDPDEF/>.

**Table 1**  
Damages in US associated with trade, 2002 (in millions of \$). Selected industries.

IO code	Sectors	Exports		Imports		Exports minus Imports		Comparisons		Net Exports (\$1million)
		DEX <sup>a</sup>	VEX <sup>b</sup>	DIM <sup>c</sup>	VIM <sup>d</sup>	$\Delta D^e$	$\Delta VA^f$	$\Delta D/\Delta VA$	$\Delta VA-\Delta D^g$	
111	Crop Production	2351	14754	2246	11020	106	3734	2.83%	3628	4368
112	Animal Production	326	1071	745	2639	-419	-1568	26.72%	-1149	-1698
113	Forestry and Logging	146	1191	105	1015	41	176	23.48%	135	155
211	Oil and gas extraction	34	2039	1521	90128	-1486	-88089	1.69%	-86603	-92322
212-213	Mining, except oil and gas	185	4298	201	3159	-16	1139	-1.40%	1155	1217
	Primary Sector Total	3060	25518	4889	116320	-1827	-90802	2.01%	-88975	-95021
221	Utilities	111	416	291	1038	-180	-621	28.95%	-441	-648
311-312	Food and beverage and tobacco products	2278	26225	2139	35413	139	-9189	-1.51%	-9328	-11418
315-316	Apparel and leather and allied products	141	5765	1236	84887	-1095	-79123	1.38%	-78028	-89656
331	Primary metals	582	8825	2298	26870	-1716	-18045	9.51%	-16329	-21806
336	Transportation Equipment	1383	98496	3113	183596	-1729	-85100	2.03%	-83371	-110970
	Secondary Sector Total	11608	422910	21272	846611	-9663	-423702	2.28%	-414039	-509490
42	Wholesale trade	381	65259	19	3299	362	61959	0.58%	61597	64159
48-49	Transportation and Warehousing	6306	58243	6354	37844	-48	20400	-0.23%	20448	21259
53	Real Estate and Rental and Leasing	170	39963	1	113	170	39850	0.43%	39680	40896
55	Management of Companies and Enterprises	147	34023	0	41	147	33981	0.43%	33834	34879
71	Arts, Entertainment and Recreation	3	888	3	162	-0.2	725	-0.03%	725.2	739
	Tertiary Sector Total	7349	282875	6559	83774	787	199098	0.40%	198311	205861
	Total	22017	731301	32722	1046705	-10705	-315405	3.39%	-304700	-398650

Shaded rows indicate sectors with negative damage to value added ratios.

<sup>a</sup>DEX denotes damages generated by producing exports.

<sup>b</sup>VEX denotes value added contribution of exports.

<sup>c</sup>DIM denotes damages avoided by importing goods and services.

<sup>d</sup>VIM denotes value added forgone due to imports.

<sup>e</sup> $\Delta D$  is the differences between DEX and DIM ( $\Delta D = DEX - DIM$ ).

<sup>f</sup> $\Delta VA$  is the difference between VEX and VIM ( $\Delta VA = VEX - VIM$ ).

<sup>g</sup> $\Delta VA - \Delta D$  is the net value added gain contribution corrected for environmental damages.

in 2002 equaled \$184 billion if expressed in 2000's prices, but approximately \$191 billion in 2002's prices. A sector level summary of GEDs by pollutants is presented in Table A9 of Appendix E. An alternative approach would be to adjust the value added and other input-output data from 2002's prices to 2000's prices. This approach requires deflators at the industry level. In the sensitivity analysis, we consider the results obtained by using the deflated IO table from WIOD, see Appendix D.

## 5. Results

### 5.1. Damages associated with trade

We present our main results for damages associated with international trade of the US in Table 1.<sup>12</sup> Let us first focus on results for a

single sector. The first row, for example, shows that the exports of Crop Products generated approximately \$2.4 billion of damages (DEX), and accounted for about \$14.8 billion of value added (VEX), in all sectors of the US taken together. If the imports of crop products would have been produced domestically instead, \$2.2 billion of damages (DIM) and \$11.0 billion of value added (VIM) would have been generated (assuming that sufficient production factors would have been available). Hence, net damages ( $\Delta D$ ) generated by trade of Crop Products amounted to \$106 million, which accounts for 2.8% of net value added created by trade ( $\Delta D/\Delta VA$ ) of crop products ( $\Delta VA = 3.7$  billion). That is, on average, for each \$1000 of value-added generated by net exports of crop products, additional air pollution would have caused \$28 of damages. In the Crop Production sector, the net exports are \$4.4 billion and the value added contained in these exports adjusted for damages from air pollutants is \$3.6 billion ( $\Delta VA - \Delta D$ ).

The sectoral ratios between DEX and VEX are not necessarily identical to the ratios between DIM and VIM, and between  $\Delta D$  and  $\Delta VA$ . For example, for Crop Products we have  $DEX/VEX = 15.93\%$ ,  $DIM/VIM = 20.38\%$ , and  $\Delta D/\Delta VA = 2.84\%$ . At the industry level, it follows from Eqs. (7)–(12) that  $DEX_{s,i}/VEX_{s,i} = DIM_{s,i}/VIM_{s,i} = \Delta D_{s,i}/$

<sup>12</sup> Table 1 only lists the results for those sectors that matter most in this respect, plus results for the three major aggregates. The complete sectoral results for all 42 sectors, can be found in Table A10 of Appendix E.

$\Delta VA_{s,i} = UD_{s,i}/u_i$ . At the sector level, however, several industries are involved in Crop Products (and in sectors selling intermediate inputs to the crops sector). The sector ratios are weighted averages of the industry ratios. The weights for DEX/VEX are the industry VEXes as share of the sector VEX, the weights for DIM/VIM are the industry VIMs as share of the sector VIM, and the weights for  $\Delta D/\Delta VA$  are the VA changes in the industries as share of the sector's VA change. The weights are thus different for the three ratios, which explains why the ratios yield different outcomes at the sector level. This also explains why  $\Delta D$  and  $\Delta VA$  have opposite signs for some sectors (corresponding to the shaded rows in Table 1). At the industry level they must have the same sign, as follows from  $\Delta D_{s,i} = UD_{s,i} \cdot (e_i - m_i)$  and  $\Delta VA_i = u_i \cdot (e_i - m_i)$ .

Shifting the focus to economy-wide effects, we find that international trade had significant environmental impacts on the 2002 US economy. The total damages associated with exports amounted to approximately \$22.0 billion, and we estimate that the total damages avoided by importing were approximately \$32.7 billion. Thus, about \$10.7 billion of damages were avoided through net imports, which can be considered as net damage benefits of trade. To put the figure of \$10.7 billion into perspective, this value is larger than the GDPs in 2002 of countries such as Iceland and Paraguay. Seen from the perspective of the US, these avoided damages could be subtracted from the structurally large trade deficit that the country has been incurring over a prolonged period of time. It accounts for 2.7% of the trade deficit (as conventionally measured, i.e. in terms of gross exports and imports) in 2002 (\$399 billion), and 3.4% of the US value added associated with trade (see Table 1).

The economy-wide damage to value added ratio of 3.4% at the national level hides a lot of heterogeneity at the detailed industry level. For instance, in the Carbon Black Manufacturing industry and the All Other Petroleum and Coal Products Manufacturing industry, damage to value added ratios were as high as 51% and 54%, respectively (see Table A11 in Appendix E). This implies that additional production by these industries (due to exports of any type of product requiring inputs from these industries) are so detrimental to the environment that more than half of its value added contributions would disappear if we would take its environmental damages properly into account.<sup>13</sup> At the more aggregated sectoral level, large but less extreme ratios are found (see Table 1), such as for Animal Production ( $\Delta D/\Delta VA = 26.72\%$ ), Forestry and Logging ( $\Delta D/\Delta VA = 23.48\%$ ), and Utilities ( $\Delta D/\Delta VA = 28.95\%$ ).

Table 1 also shows that net environmental benefits (or costs) associated with trade differ significantly among sectors. Consider the three broad sectoral aggregates, for example. Net trade in products from the primary sector led to a reduction of about \$1.8 billion of damages, while these amounted to about \$9.7 billion for trade in products of the secondary sector. Net trade in products of the tertiary sector, however, added to environmental damages by about \$0.8 billion. Furthermore, the damage to value added ratios differed to a large extent. For the primary and secondary sectors, these were larger than 2%, while they amounted to less than 0.5% of value added in the tertiary sectors.

Table 1 shows that the largest net environmental benefits were generated by trade in products from the Transportation Equipment, Primary Metals, Oil and Gas Extraction, and Apparel and Leather and allied Products sectors, with avoided damages of \$1.7 billion, \$1.7 billion, \$1.5 billion, and \$1.1 billion, respectively. The largest net environmental costs of trade were generated by exports of the Wholesale trade sector (−\$362 million), followed by those of the Real Estate and Rental and Leasing (−\$170 million), the Management of Companies and Enterprises (−\$147 million), the Food and Beverage, Tobacco Product (−\$139 million), and the Crop Production (−\$106 million) sectors.<sup>14</sup>

<sup>13</sup> Damage to value added ratios at the industry level are available from the author upon request.

<sup>14</sup> The top 10 and bottom 10 industries regarding  $\Delta D$  for each pollutant are

## 5.2. Unit damages

We also find that the signs of the net damages did not always correspond to the signs of net exports. This shows that a trade deficit does not automatically imply damage benefits. The four sectors for which we find such a negative damage to value added ratio are highlighted in Table 1. For instance, we find that the US had a trade surplus in products from the Transportation and Warehousing sector (\$21.3 billion). Trade in these products generated a positive net effect on value added ( $\Delta VA = \$20.4$  billion) but a negative net effect on the damages ( $\Delta D = -\$48$  million). Trade thus leads to more income and less damages. Similar findings are observed for the Mining, Except Oil and Gas sector, and the Arts, and Entertainment and Recreation sector. The opposite effect (trade induces less income but more damages) is observed for the Food, Beverage, and Tobacco Products sector. Everything else equal, it is—for the net effect on damages—beneficial for a country to import products with high unit damages and exports products with low unit damages.<sup>15</sup> We calculated these unit damages (defined as damages generated by \$1000 exports or avoided by \$1000 imports). In Table 2, we present these unit damages at the sectoral level.<sup>16</sup>

Not surprisingly, we find that an increase of exports by the tertiary sector would yield much smaller damages than if exports of the primary sector would increase by the same amount. However, the damages avoided by importing more tertiary products are larger than those avoided by increasing the imports of products from primary industries by the same value. This at first sight surprising result is mainly due to the importance of damage-intensive crops in the US's export bundle of primary products, while it is much less prominent in the import bundle of these products. In this import bundle, the output of the Oil and Gas Extraction industry (which generates much less damages per \$1000 of imports than imports of other primary products) accounts for a much larger share.

Concerns have been voiced about so-called “pollution haven” effects. Polluting industries would relocate outside the US to save on costs incurred to comply with environmental regulations. Our data do not allow for a longitudinal analysis required to arrive at strong evidence, but a finding of more damaging imports than exports would provide a hint into this direction. Table 2, shows that the damages were \$26.69 per \$1000 of imports and \$26.63 per \$1000 of exports. This negligible difference suggests that multinational companies had not massively relocated damaging activities from the US to other countries in 2002. Still, a few more caveats apply. First, we implicitly assume that US industries conduct the same activities as their foreign counterparts. This is not necessarily true. The US Computer and Electronic Products industry has specialized in R&D, design and marketing activities, while the manufacturing activities mainly take place in various Asian countries (see e.g. Dedrick et al., 2010). These activities have very different impacts on the environment. Second, international trade in intermediate inputs started booming after 2001, in the so-called “second wave” of globalization (which also included the emergence of China as a location for manufacturing activities) (see Baldwin, 2016). Hence, we cannot generalize the absence of “pollution haven” effects to recent periods.

Trade surpluses and deficits are defined in terms of gross exports and imports and are therefore different from the net value added generation due to exports and imports, as explained in Section 3. One might develop a trade strategy to maximize the gains and minimize the

(footnote continued)

presented in Tables A12 and A13 of Appendix E.

<sup>15</sup> In the same fashion, everything else equal, it is—for the net effect on value added—beneficial for a country to export products with high unit VA and import products with low unit VA.

<sup>16</sup> The top-10 and bottom-10 industry level “unit damages” are presented in Table A14 in Appendix E.

**Table 2**

Unit damages of trade (\$ damages per \$1000 of exports or imports) by sector.

IO code	Sectors	Exports			Imports			Net exports (\$1million)
		%Exports	\$ Damages per \$1000 of exports		%Imports	\$ Damages per \$1000 of imports		
		(Weights)	Total	\$Damages of intermediate products in the other sectors (% of total)	(Weights)	Total	\$Damages of intermediate products in the other sectors (% of total)	
111	Crop Production	2.00%	145.22	21.67 (14.92%)	1.00%	189.94	19.65 (10.35%)	4368
113	Forestry and Logging	0.20%	116.71	35.06 (30.04%)	0.10%	95.64	23.81 (25.05%)	155
211	Oil and Gas Extraction	0.30%	16.10	8.80 (54.66%)	7.70%	16.10	8.80 (54.66%)	-92322
212-213	Mining, Except Oil and Gas	0.60%	40.36	23.58 (58.42%)	0.30%	59.63	24.87 (41.71%)	1217
Primary Sector Total		3.30%	110.62	21.11 (19.08%)	10.00%	39.85	11.14 (27.95%)	-95021
221	Utilities	0.10%	253.35	8.37 (3.30%)	0.10%	267.72	7.68 (2.87%)	-648
311-312	Food and Beverage and Tobacco Products	3.50%	78.35	72.91 (93.06%)	3.30%	52.83	48.41 (91.63%)	-11418
315-316	Apparel and Leather and Allied Products	0.80%	21.74	21.30 (97.98%)	7.80%	12.86	12.65 (98.37)	-89656
325	Chemical Products	7.80%	36.19	21.59 (59.66%)	8.20%	24.59	14.23 (57.87%)	-36448
331	Primary Metals	1.30%	54.06	27.16 (50.24%)	2.70%	70.55	29.04 (41.16%)	-21806
333	Machinery	7.10%	11.90	11.41 (95.88%)	5.30%	11.88	11.38 (95.79%)	-6617
334	Computer and Electronic Products	12.10%	8.45	8.24 (97.51%)	14.50%	7.74	7.60 (98.19%)	-77435
336	Transportation Equipment	14.40%	11.63	10.67 (91.75%)	18.70%	13.54	11.40 (84.19%)	-110970
Secondary Sector Total		60.20%	23.29	17.44 (74.88%)	82.20%	21.10	14.86 (70.43%)	-509490
42	Wholesale trade	8.16%	5.64	4.20 (74.47%)	0.28%	5.64	4.20 (74.47%)	64159
4A	Retail Trade	8.03%	9.05	7.33 (80.99%)	3.69%	9.05	7.33 (80.99%)	-2416
48-49	Transportation and Warehousing	0.10%	94.84	8.19 (8.64%)	0.27%	140.47	8.64 (6.15%)	21259
52	Finance and Insurance	4.57%	2.18	2.18 (100%)	2.24%	1.89	1.89 (100%)	10441
53	Real Estate and Rental and Leasing	4.95%	4.15	4.15 (100%)	0.01%	4.58	4.56 (99.56%)	40896
61	Educational Services	0.05%	18.01	18.01 (100%)	0.02%	18.10	18.10 (100%)	164
71	Arts, Entertainment and Recreation	0.11%	3.44	2.87 (83.43%)	0.01%	19.94	6.06 (39.39%)	739
Tertiary Sector Total		36.50%	24.44	4.87 (19.93%)	7.80%	68.40	5.97 (8.73%)	205861
Total		100%	26.63	12.98 (48.74%)	100%	26.69	13.79 (51.67%)	-398650

Note: The primary sectors, secondary sectors, and tertiary sectors are separated by horizontal lines. Selected sectors are included in this table. Please see Tables A4.15 and A4.16 in Appendix E of “unit damage” with respect to exports and imports of all sectors by pollutants. The shaded rows indicate sectors in which more than 80% of the damages (associated with imports or exports) come from intermediate products in other sectors.

losses, leaving the trade balance the same. Importing from industries with high unit damage (\$ damage per \$1000 dollar of imports or exports) and exporting in industries with low unit damage will lower the losses. At the sector level, Table 2 showed that Crop Production and Machinery qualify as such. Importing an additional billion dollar of

crop products and increasing exports machinery products by the same amount would have yielded lower losses (i.e. damages) and more gains (i.e. value added) in the US, while leaving the trade deficit unchanged.

Table 2 also shows that damages associated with producing intermediate products (products that are not exported themselves but are



used to produce exported products) are considerable. For instance, we find that virtually all damages associated with trades in three major service sectors (Finance and Insurance, Real Estate and Education Services) are generated in the production of intermediate products. At the national level, damages associated with intermediate products account for about half of the total “unit damage” of both exports and imports (49% and 52%, respectively). If intermediate products would not be taken into consideration, the unit damages of imports and exports would be more than 80% lower in as many as nine sectors: Food and Beverage and Tobacco Products, Apparel and Leather and Allied Products, Machinery, Computer and Electronic Products, Transportation Equipment, Retail Trade, Finance and Insurance, Real Estate, and Education Services. This is to an important extent due to the fact that these sectors require electricity to produce. Power generation (which is part of the sector Utilities) is a very damaging activity, which is reflected in the very high unit damages of this sector reported in Table 2. A substantial part of the damages embodied in the exports of a product is thus associated with the production of its intermediate products. This finding indicates that it is important to study damages in trade in an input-output (IO) analysis. Next to the direct effects of trade, IO studies also take all indirect effects into full account.

### 5.3. Damages by pollutant

In Fig. 2, we present a pie chart to show the composition of the net \$10.7 billion environmental benefits of US trade in 2002, by pollutant. SO<sub>2</sub> was clearly the most important pollutant. It accounted for almost half of total  $\Delta D$  (48%), followed by fine particles (PM<sub>2.5</sub>) and volatile organic compounds (VOC). Through international trade, about \$5 billion of damages caused by SO<sub>2</sub> were avoided. Tables A13 in Appendix E shows that most of the trade related damages were clustered in trade and transportation sectors. Other sectors in the top-10 of sectors with damaging SO<sub>2</sub>-related effects of net trade include other services sectors, farming and (in particular) manufacturing sectors.

With respect to the Animal Production sector and the Forestry and Logging sector, NH<sub>3</sub> is responsible for more than 85% of damages related to both exports and imports. We also find that NH<sub>3</sub> emissions were particularly important regarding trade in products of some manufacturing sectors, such as the Food and Beverage and Tobacco Products and the Wood Products sectors, which are highly dependent on agricultural inputs.

## 6. Sensitivity analysis

As discussed in Section 4, we had to make several choices with respect to the data. Each of these choices could have impacts on the

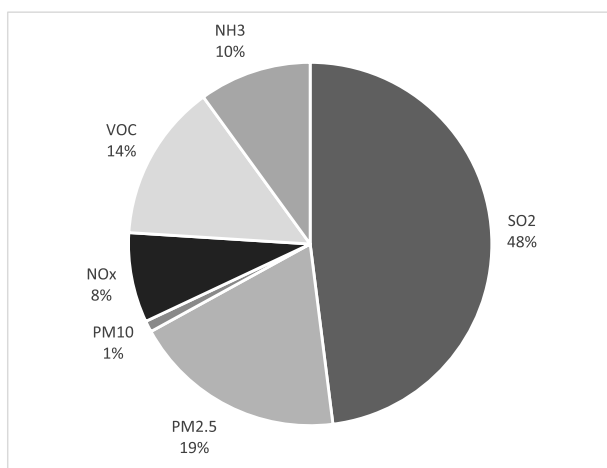


Fig. 2. Composition of the damages of net trade ( $\Delta D$ ) by pollutant.

Table 3  
Sensitivity analyses.

Cases	Description	$\Delta D$ (\$1 M)	$\Delta D/\Delta VA$
Case I	Baseline	-10,705	3.39%
Case II	Foreign border prices	-9446	3.43%
Case III	Split by output	-9989	3.17%
Case IV	No missing damages	-10,414	3.31%
Case V	Basic prices 2002	-8898	2.84%
Case VI	Basic prices 2000	-8550	2.65%
Case VII	Laden	-11,883	3.77%
Case VIII	VSL6m	-12,243	3.88%
Case IX	VSLY2m	-10,052	3.19%
Case X	VSLY10m	-11,339	3.59%

Note:  $\Delta D$  is negative, because there are more damages avoided by imports than damages generated by exports. Case I is the baseline model. Case II excludes costs of duties, freight and insurance from the imports. Case III splits the GED of agricultural and construction industries by gross output. Case IV estimates some missing damage values using data from other industries producing similar goods or services. Case V uses IO data from WIOD in basic prices. Case VI uses IO data from WIOD in basic prices and deflated IO data from 2002 to 2000. Case VII uses the adult mortality dose-response function for PM<sub>2.5</sub> from Laden et al. (2006). Case VIII employs the same value for premature mortality to the populations of all ages. Case IX changes the Value per Statistical Life (VSL) to \$2 million. Case X changes the VSL to \$10 million. Cases I, VI and VII employ premature mortality values that are heterogeneous across ages.

results. In this section, we redo the analysis nine times (Case II to Case X) with approaches or assumptions different from the baseline model (Case I, in what follows), for which we have already reported the results. Case II, Case V and Case VI address the issues regarding prices. Case III and Case VI deal with the industrial GED data issues. Cases VII to X deal with assumptions with respect to the marginal damage estimation in Muller et al. (2011). Summary results of these sensitivity analyses are presented in Table 3.

In Case II, we value imports at foreign border prices instead of the US border prices, to assess the sensitivity of results to differences in price concepts. The foreign border prices are roughly equal to the ex-factory price plus the margins for transport and trade within the exporter country. The US border prices employed in the baseline model is equal to the foreign border values plus the freight, insurances, and custom duties associated with international trade. Hence, for a given quantity of imported products, values of imports are smaller if the foreign border prices are employed. Consequently, we find smaller values of damages and lower value added associated with these imports. Given that we assume that everything else is the same, the net damage avoided by trade is lower than as found in the baseline model. In the baseline model (or Case I), we found that \$10.7 billion net damages were avoided by trade. This value is reduced to \$9.4 billion in Case II, which implies a difference of about 12%. If we focus on the  $\Delta D/\Delta VA$  ratio, however, the difference is very small: 3.39% in Case I versus 3.43% in Case II.

As we mentioned in Section 4, we had to disaggregate GED values with regard to some agricultural industries and construction industries. In the baseline model, the disaggregation of agricultural industries is carried out proportionally to value added by industry. In some other studies, gross output shares have been employed instead. Therefore, in Case III, we change the disaggregation approach by using gross output shares (see Tables A7a and A7b of the Appendix D). We find the  $\Delta D$  is -\$10.0 billion in Case III, which implies that the avoided damages are \$716 million smaller than in Case I. The  $\Delta D/\Delta VA$  ratio is 3.17%, which is 0.22% lower than the ratio in Case I.

Another issue relates to the fact that we do not have information on GED values in 20 industries. Among them, 18 are industries in the tertiary sector. In the baseline analysis, we assumed that the gross environmental damages of these industries are zero. In Case IV we analyze the sensitivity of the results to this choice, by assuming that the unknown damage intensities ( $GED_i/x_i$ ) are equal to those of industries

producing similar goods or services. For instance, we assume that the damage per unit of output in the Tortilla Manufacturing industry is the same as the damage per unit of output in the Cookie, Cracker and Pasta Manufacturing industry.<sup>17</sup> Case IV gives very similar results compared to the baseline model. Both the avoided damages and the overall  $\Delta D/\Delta VA$  ratio are slightly smaller than in the baseline model ( $-\$10.4$  billion and 3.31%, respectively).

In Case V, we assess the sensitivity of our results to the choice of price concept by using IO data in basic prices, which are obtained from WIOD (Dietzenbacher et al., 2013). On the one hand, basic prices (which exclude taxes and subsidies from producer prices) are the preferred type of prices. On the other hand, the WIOD tables are more aggregated, distinguishing only 35 sectors. Moreover, the sector classification is aligned with the European NACE, which implies that we need to match damage data for North-American NAICS sectors to NACE sectors. To this end, we used a conversion table from the US Census Bureau.<sup>18</sup> Table 3 shows that the US avoided \$8.9 billion of damages by trading according to this analysis, which is \$1.8 billion or 17% less than in Case I (the baseline). The reduction in value added is also much less (30%) in Case V than it is in Case I. The economy-wide  $\Delta D/\Delta VA$  ratio is therefore 0.55% lower if based on WIOD. It is not straightforward to compare sectoral results from Case V to those from the baseline model, because of the different classification systems.<sup>19</sup> Nevertheless, we find that the  $\Delta D/\Delta VA$  ratios are fairly close in many sectors (see Tables A17 and A18 in Appendix E). The  $\Delta D/\Delta VA$  ratios of Electricity, Gas and Water Supply (Case V) and the Utility sector (Case I) are both around 29%, and these ratios are close to 0.55% for the Wholesale Trade sector in both tables. The  $\Delta D/\Delta VA$  ratios are also fairly close in sectors related to textile products, wood products, transportation equipment, accommodation and food services (hotel and restaurants), financial intermediates, real estate activities, and education. However, for some sectors heavily involved in trade, like Petroleum and Coal products, the differences are sizable (7.73% in Case I, but only 3.65% in Case V).

In all the cases we discussed so far, the estimation results are in 2002's prices. Recall that the original damage data (for 2002) are in prices of 2000 and have been converted to prices of 2002 with a GDP deflator. In Case VI, we keep damage data in 2000's prices, but convert IO data from 2002's prices to 2000's prices. For this, we used data from WIOD and applied the "chaining technique" explained in Appendix D. Data from the WIOD is in basic prices, so the basic prices are used in Case VI as well. The estimated total net damages in Case VI are only slightly smaller than in Case V, and the  $\Delta D/\Delta VA$  ratios of Cases V and VI are quite close. The results thus appear to be insensitive to the way in which deflation is done.

Cases VII to X follow Muller et al. (2011) in assessing the effects of uncertainties in marginal damages, regarding three aspects. First, the  $PM_{2.5}$  mortality dose-response function from Pope et al. (2002) is used in the baseline estimates. In Case VII, we use a more sensitive dose-response function, from Laden et al. (2006). As a result, the total damages avoided by trade move up to \$11.9 billion, and the overall ratio of  $\Delta D/\Delta VA$  increases to 3.77%. Second, in the baseline model, we assume that the costs of premature mortality varies with age.<sup>20</sup> In Case VIII, the value of premature mortality is assumed to be identical across ages. This change raises the value of damages avoided by trade to \$12.2

billion and the overall  $\Delta D/\Delta VA$  ratio to 3.88%, which are the highest among all cases. Third, in the baseline model, the value of statistical life (VSL) (Viscusi and Aldy, 2003) equals \$6 million, and this VSL value is used to determine the annual mortality risk premium (Muller et al., 2011). In Case IX, we assume the VSL equals \$2 million (following Mrozek and Taylor, 2002), which leads to a reduction of the avoided damages by \$653 million. In Case X, we assume that the VSL equals \$10 million (following Viscusi and Moore, 1989). This causes an increase in the avoided damages by \$634 million.

Summarizing the cases, we find that the estimated values of US-wide damages avoided by trade vary from \$8.6 billion to \$12.2 billion, which correspond to deviations from the baseline model between  $-17\%$  and  $+14\%$ . The overall  $\Delta D/\Delta VA$  ratio ranges from 2.65% to 3.88%. In most sectors, the differences between the sectoral  $\Delta D/\Delta VA$  ratios across cases are small (see Tables A17 to A19 in the Appendix E), and the relative rankings across sectors remain roughly the same under different assumptions. Although the magnitudes of the welfare impacts vary, we consider the results from the baseline model as good indications, in particular with respect to the  $\Delta D/\Delta VA$  ratios.

## 7. Conclusions

This study estimated the monetary values of the health and social-economic impacts associated with emissions generated in activities required for US exports by trade and the emissions on US territory that are avoided by importing products. Using these monetary values allowed us to compare damages with economic effects of trade, and to compute trade balance indicators with a wider scope. Here, we summarize some key findings.

First, damages associated with international trade are considerable and cannot be neglected. For 2002, we found that the US avoided \$32.7 billion of damages by importing, and at the same time generated \$22.0 billion of damages to produce its exports (both directly by exporting industries, and indirectly by domestic suppliers of these industries). This implied that the net trade effect was a reduction of damages caused by emissions to air of about \$10.7 billion in 2002. Economy-wide, every \$1000 of net value added generated by trade caused emission-related net damages of \$33.9 on average. At the industry level, we found that such damage to value added ratios can exceed 50%, such as in the Carbon Black Manufacturing (51%) and the All the Other Petroleum and Coal Products Manufacturing industry (54%). However, in other industries, such as Legal Services, only \$2 of damages were associated with \$1000 of value added generated by trade.

Second, a considerable amount of damage was generated through the production of intermediate products, so it is important to use input-output analysis in this study. Damages associated with emissions by producers of intermediate inputs embodied in US exports (and in imported products if they would have been produced domestically) accounted for about half of the total "unit damage": \$12.98 out of \$26.63 of damages in an average \$1000 of exports and \$13.79 out of \$26.69 of damages in an average \$1000 of imports.

The finding that the US avoided more damages on its own territory by importing than that it generated to produce its exports is strongly related to its massive trade deficit. Still, we found that for some sectors a trade deficit and positive damages due to trade coexisted. The US had a trade deficit of \$11.4 billion regarding products of the Food, Beverage, and Tobacco Product sector, for example, but net trade in these products generated a net effect of \$139 million damages. This is the consequence of differences in the compositions of imports and exports. Even within rather homogeneous sectors, products sold by industries (defined at a more fine-grained level) can vary considerably in terms of the damages they cause.

We did some sensitivity analyses regarding assumptions with respect to price concepts, missing data, and the marginal monetary damage value of emissions. We found that the sensitivity of the results to some of the assumptions is not negligible, in the sense that the net effect

<sup>17</sup> The selected "proxy industries" and the estimated damages per dollar of output are presented in Table A8 of Appendix D.

<sup>18</sup> The table can be obtained from <https://www.census.gov/eos/www/naics>.

<sup>19</sup> Additional errors might be introduced during the conversion of damage data from NAICS codes to NACE codes (the match is not perfect), and estimation results can be less accurate because a relatively aggregated input-output table is employed.

<sup>20</sup> For example, the mortality value faced by elderly people is relatively low, because they have fewer life-years remaining. However, this assumption is controversial. One could also argue that the value society places on mortality risks should not vary by age.

of both the damages and the value added generation can change by about 15% in either direction, in particular if different price concepts are used in the valuation of economic transactions. However, differences in the damage to value added ratios are rather small at the economy-wide level and small to moderate in most sectors.

Currently, the persistent and large trade deficit of the United States attracts a lot of attention, both in policy circles and among academic scholars. Although this trade deficit is the direct consequence of low savings by Americans, President Trump feels that he can reduce it by import substitution policies, mainly implemented via high tariffs that might lead to a trade war with countries like China. This study shows that the true US trade deficit is about 3% smaller if the costs of pollution to society are taken into account. By importing much more than exporting, the US avoids pollution-related damages that it would have incurred if the imported products would have been produced in the country itself. In their attempts to curb imports by means of tariffs, policymakers could take such damages into account.

Future research along the lines set out in this study is definitely possible. First, only damages from emissions to air are included in this study. Other external effects, such as damages related to pollution of water and soil, or to noise, are not taken into account. Second, at the time this study was carried out, damages occurred in years more recent than 2002 could not be assessed due to data availability.<sup>21</sup> Finally, we focused on damages related to trade in the US, because there is no marginal damage data on emissions in the other countries. If such data would be available, we could consider trade as a worldwide phenomenon and study whether its environmental consequences in monetary terms are positive or negative.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Appendix. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ecolecon.2020.106599>.

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<sup>21</sup> According to Muller (2018), more recent damage data are available for the years 2005, 2008 and 2011.